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Strategic Oil Dependence

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Abstract

In the oil market large sellers and their cartel communicate like central bankers, emphasizing credibility and security of supply. Why is this? We analyze sellers' supply policies when future demand is intertwined with consumers' interest in ending the relationship. We show that strategic sellers maintain resource-dependence by increasing supplies from declining reserves. When the size of the remaining resource is only privately observed, policies of secure supply can exploit buyers' imperfect information and imply a risk of future supply shock. This suggests a new perspective to sellers' strategic behavior in the oil market.

JEL Classification: D4; D9; O33; Q40.

Keywords: dynamic bilateral monopoly, Markov-perfect equilibrium, depletable resources, energy, alternative fuels, oil dependence.

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1 Introduction

In the oil market, the sellers' cartel and large suppliers communicate like central bankers with the market, emphasizing credibility and security of supply. Why do sellers care about the security of supply? In this paper, we analyze how producers manage their demand given the buyers' interest in ending their dependence on producers' supply. Such interests are prevalent as demand side policies reduce macroeconomic risks and environmental externalities. Policies also exploit network externalities, so that energy infrastructure choices are often seen to require centralized decision making. Given concerns over global warming, these interests are also intergovernmental and they aim at an economy-wide change in the energy demand infrastructure. In such a market, producers' perception of future demand becomes intertwined with the buyers' interest in ending the relationship, and it is no longer clear that even a coherent seller side would see the traditional restricted-supplies policy as its best-interest policy.[1] For public policy in oil-importing countries, it is important to understand not only the risks of continued resource dependence, but also the sellers' effort to distort the buyers' decision on ending the relationship.

The economic nature of the relationship between major oil-importers and exporters such as United States and Saudi Arabia is clearly not a direct bargaining situation, as international contracts are not conceivable in this context. However, the relationship has a flavor of bargaining taking place through markets. Sellers' focus on secure supply suggests a compensation to the importing party for continuing potentially costly dependence. On the buyer side, trust in the relationship is expressed by voluntary inaction, that is, postponement of actions changing the demand structure. It seems clear that the sellers' concern for security of supply will be different once the buyer side has committed resources to activities that aim at ending the dependence on supply in the foreseeable future. To capture elementary properties of such a market-based bargaining, we model it as a bilateral monopoly situation where one side coordinates on supplies and the other on timing of change of the demand infrastructure.

We find that the relationship must become more costly over time, because the resource available for a potentially long transition towards substitute supplies is depleted.

[1] The following citation describes the concern: "We've got almost 30 percent of the world's oil. For us, the objective is to assure that oil remains an economically competitive source of energy. Oil prices that are too high reduce demand growth for oil and encourage the development of alternative energy sources" (Adel al-Jubeir, foreign policy adviser of crown prince Abdullah of Saudi Arabia, Herald Tribune, Jan 24, 2007).

Producers have to compensate buyers for increasing costs, and therefore the seller side has to *supply larger quantities from declining stocks* to postpone the start of the technology transition. The result is in sharp contradiction with the standard prediction that greater scarcity leads to lower supplies, but it follows quite naturally if one expects that finiteness of supply increases costs during the transition towards the demand change.

In connection with oil, it is clear that the world will never run out of all fossil fuel sources when we include unconventional oils, tar sands, and coal, but it is equally clear that we may run out of conventional, cheap oil. The resource that, for example, Saudi Arabia is controlling is unique in that it allows extraction of high quality output with relatively little capital investment. It also allows for rapid and large production rate changes. Reserves with such properties are at the heart of the economics of the oil dependence because, roughly put, the remainder of the fossil fuel supply is capital intensive and costly when used for the production of liquid fuels. In fact, what is essential for the strategic interaction between the seller and buyer is the existence of a very competitive but finite reserve with inelastic short-run demand; the rest of 'oil' production can be seen as part of substitute fuel production, including nonconventional oils, biofuels, and alternative energy sources.[2]

Though being very competitive, the core conventional oil stocks are not managed like most productive assets in market economies. The dynasties of the Middle East do not disclose technical production information and make efforts to prevent auditing of the reserves. The future availability of conventional oil is a major public concern in oil importing countries, and industry experts' opinions on the size of economically viable stocks diverge widely.[3] This informational asymmetry is a potential risk associated with OPEC's role as the central banker of the oil market. We find that when the size of the remaining reserve is only privately observed by the seller side, there is an incentive to exploit the buyers' imperfect information for right timing of the demand change. We describe an equilibrium with a persistent possibility of a price shock as the seller side hides true reserves by currently supplying large quantities postponing buyers' action to a

[2] The difference between conventional and nonconventional oils is concisely explained in the Hirsch Report (prepared for the U.S. Department of Energy, 2005). The report also makes clear that the important scarcity is in the reserves of high-quality conventional oil.

[3] These concerns are reviewed in the Hirsch report. A book by Matthew R. Simmons (2005) explicates carefully the industry experts concerns regarding the Saudi stocks. In particular, Saudies have not disclosed technical production information since the early 1980. Therefore, the maturity of the main Saudi stocks (six main oil fields) cannot be addressed, leading to concerns that suppliers cannot expand production further in the near future.

point that makes the technology transition period an era of scarcity. This suggests a risk in the relationship: continued resource dependence delegates the timing of the demand change to the informed party, that is, to the seller, who initiates the change through the revelation of the true scarcity.

Our research departs from previous literature on the topic by allowing a market structure with implicit offers and responses such that no party is in explicit leadership. In particular, the structure preserves the nature of the strategic interaction in the limiting case without discounting, which allows an essentially static analysis and it shows the way to analyze the discounted case. The reduction in the dynamic dimension also enables us to analyze the asymmetric information case, which is nonexisting in the literature. Moreover, in addition to market structure assumptions and asymmetric information, we depart from previous literature in that we abstract from the precise instrument implementing the structural change: when action is taken, it changes the demand irreversibly after a time lag. This abstraction simplifies the strategic variable on the buyer side while keeping what seems material in the relationship.

Previous literature can be divided on the assumptions made for the strategic variable on the buyer's side. First, there is a large literature on optimal tariffs in depletable-resource markets showing how coordinated action on the buyer side can be used to decrease the seller's resource rent (e.g., Newbery, 1983, Maskin and Newbery, 1990; see Karp and Newbery 1993 for a review). While import tariffs and fuel taxes are important, they are more flexible instruments as compared to the development of substitute technologies that have a permanent effect on the resource dependence. The latter thus creates potentially greater or at least very different strategic threats for the seller. To be effective, the optimal tariffs have to be successful in changing the dynamic demand perceived by the seller. The degree of success obviously depends on the precise formulation of the game, but generally the seller's sales path still follows a Hotelling rule modified to take into account the buyers' tariff policy. This leads to supplies declining over time. We believe that the technology threat potentially is a more important determinant of how sellers perceive their future demand.

Second, there is a large but somewhat dated literature on the same bilateral monopoly situation where the buyers' strategic variable is to develop or adopt a substitute technology. Early papers such as Dasgupta *et al.* (1983), Gallini *et al.* (1983), and Hoel (1983) assume the buyers exploit a Stackelberg leadership and commit to a deterministic R&D program for the development of the substitute. The results provide interesting insights into how the buyer side can extract the seller's rent by altering the timing of sales. Later developments analyzed the role of leadership and commitment (Lewis *et al.*, 1986) and, finally, probabilistic success in R&D and Markov-perfect strategies (Harris and Vickers, 1995). None of the above papers predict that supplies from declining stocks increase over time.[4]

The structure of the paper is the following. In Section 2, we introduce the basic resource allocation problem by considering the social optimum and consumers' optimum. In Section 3, we introduce and analyze the game under perfect information. In Section 4, we extend the basic model to the incomplete information case. In Section 5, the deterministic version of the model is extended to include discounting. In Section 6, we conclude by discussing alternative approaches to the problem and potential implications for the oil market.

2 Optimal resource dependence

Before going to strategic interactions, we start the analysis by looking at socially optimal resource use. This way we will introduce the basic elements of the model and provide a benchmark so that distortions introduced by strategic market interactions become clear.

Consider an economy starting at time $t = 0$ with a finite resource endowment s_0 that can be consumed at rate q_t yielding a strictly concave utility $\widetilde{u}(q_t)$. The resource has a substitute that provides the same service and ends the need to use the resource. The economy can choose to adopt the substitute by paying one-time cost $I > 0$ at any t, wait for k periods so that the alternative replaces the resource at $t + k$, and then pay ongoing cost $c > 0$ per period for using the substitute. We deliberately abstract from precise actions implementing the change in demand because the focus is on the following trade-off: how much of the resource should be used before actions are taken, and how much should be left for the transition period towards the substitute? Introducing extraction cost for the resource, reducing irreversibility of the change in demand, or including uncertainty regarding success of the process do affect the precise answer to the trade-off. However, that the substitute is costly and that it takes time to build up the new demand infrastructure are the two assumptions that capture most of the action in the strategic interaction.

To describe the social optimum, it is useful to treat the period over which there is some resource consumption as an excursion from the long-run situation where the

[4] Harris and Vickers (1995) obtain a result that sales path may be non-monotonic but it is not generically increasing.

substitute is present and consumers enjoy surplus $\bar{u}$ per period. The consumer price is $p_t = \psi(q_t) = \widetilde{u}'(q_t)$, and demand is $q = D(p) = \psi^{-1}(p)$, so we can write the long-run surplus flow as

$$\bar{u} = \widetilde{u}(D(0)) - c.$$

The substitute thus replaces the resource fully.[5] For future reference, we separate the consumers and producers overall surplus from resource consumption. Sellers' flow profit is $\pi(q) = \psi(q)q$ and assumed to be strictly concave. Consumers' surplus is $u(q) = \widetilde{u}(q) - \pi(q)$, and need not be concave.[6] We assume that surplus $u(q)$ is everywhere nonlinear,[7] differentiable, and bounded at some level above $\bar{u}$. The resource can thus provide surplus above the long-run level. Throughout the paper we assume that stock s_0 is large enough, so that actions to end resource consumption are not taken at $t = 0$.

We assume no discounting for now.[8] We denote the seller's stock-dependent payoff by $V(s_t)$ and consumers' payoff by $W(s_t)$ if there has been no investment before t. Expression $V(s_t)$ measures cumulative (undiscounted) future profits while $W(s_t)$ measures cumulative surplus from the excursion above the long-run surplus from period t onwards:[9]

$$V(s_t) = \int_t^{T+k} \pi(q_\tau) d\tau \tag{1}$$

$$W(s_t) = \int_t^{T+k} [u(q_\tau) - \overline{u}] d\tau \tag{2}$$

The social optimum depends on the period of resource use, $T + k$, and the supply path q_t, that maximizes total resource surplus

$$\mathcal{W}(s_t) = V(s_t) + W(s_t) = \int_t^{T+k} [\widetilde{u}(q_\tau) - \overline{u}] d\tau \tag{3}$$

[5] The assumption is made for the ease of exposition but we also think it reflects some realism. Alternatively, we can assume extraction costs and that the cost of using the substitute are lower.

[6] Consumer surplus will be a central determinant of the buyer's investment decision, so we have to be specific about it. For example, under linear demand, $u(q)$ is convex on $[0, D(0)]$ and constant thereafter. For constant relative risk aversion (CRRA) utility functions, $u(q)$ is concave for all values of the coefficient of relative risk aversion.

[7] That is, there is no non-empty interval (a, b), with $a < b$, such that $u(q)$ is linear over (a, b).

[8] In Section 5, we extend the model to positive discounting.

[9] Since the seller makes zero profit in the long-run, his payoff can also be interpreted as the value of excursion above the long-run payoff. Note that we are adopting the Dutta's (1991) strong long-run average criterion. Therefore, we can anticipate already at this point that the undiscounted equilibrium is a true discounted equilibrium limit. This will be verified in section 4.

Notice that we leave the investment costs out of the welfare function since, without discounting, the timing of investment has no bearing on the net present value of its costs. The following lemma is immediate.

Lemma 1 *Along a social-optimal path, $\mathcal{W}(s)$ is linear, i.e., $\mathcal{W}(s_0) = \lambda s_0$ for some constant λ.*

Proof. The proof is by contradiction. Suppose $\mathcal{W}(s)$ is not linear, so we have s_0^a and s_0^b with $\mathcal{W}(s_0^a) = \lambda^a s_0^a$, $\mathcal{W}(s_0^b) = \lambda^b s_0^b$, and $\lambda^a \neq \lambda^b$, while in both cases $T > 0$ by assumption. Without loss of generality, assume $\lambda^a > \lambda^b$. Now, we note that due to concavity of $\widetilde{u}(.)$ the optimal q_t is a constant path over a period $[0, T_a + k]$ and we stretch out (or shrink) the optimal path q_t^a that produces $\mathcal{W}(s_0^a)$, to generate a path for case b: $q^* = q_t^a$, over a period with $T_b + k = (s_0^b/s_0^a)(T_a + k)$. It is obvious that this path q^* produces welfare $\lambda^a s_0^b$. Thus, the optimal path for s_0^b must produce at least the same welfare level: $\mathcal{W}(s_0^b) = \lambda^b s_0^b \geq \lambda^a s_0^b$, which contradicts the assumption of $\lambda^a > \lambda^b$. ■

The variable λ measures the marginal value of the resource, $\mathcal{W}'(s_0^a) = \lambda$. Surplus maximization can thus be implemented as the maximization of the (marginal) value of the resource λ, independent of time and level of the resource. Consider a short period ε with continuous supply q_t. Resource use over this period is εq_t. Welfare accumulated over this period is $\varepsilon[\widetilde{u}(q_t) - \overline{u}] = \lambda \varepsilon q_t$. The marginal value of the resource is $\lambda = [\widetilde{u}(q_t) - \overline{u}]/q_t$, and the surplus maximization is thus equivalent to maximizing the average excursion above the long-run payoff. It is instructive to see Figure 1, where we can find the social optimal supply level $q = q^{**}$ on the curve of utility $\widetilde{u}(q)$ such that the line through $(0, \overline{u})$ and $(q, \widetilde{u}(q))$ has the steepest slope.[10] Recall that utility $\widetilde{u}(q)$ is concave, and thus q^{**} must also satisfy

$$\widetilde{u}(q^{**}) = \overline{u} + q^{**}\widetilde{u}'(q^{**}).$$

Since consumer surplus is $u(q) = \widetilde{u}(q) - q\widetilde{u}'(q)$, we must have

$$u(q^{**}) = \overline{u}. \tag{4}$$

Proposition 1 *In the social optimum, consumers receive reservation utility level $\overline{u}$ in all stages, while producers receive all the resource surplus. Consumers do not benefit from an increase in the resource stock, $W'(s_0) = 0$.*

[10] We use one asterisk for equilibrium constants, and two asterisks for social optimum constants. Some equilibrium constants are first presented as part of the buyer's optimum, and these are therefore also denoted by one asterisk.

Proof. The first part of the proposition states that along the social optimal path, the buyer is indifferent between resource dependence and the substitute technology. This part follows immediately from (4). The last part of the proposition then follows from the definition of the buyer's payoff (2). ■

Consider what would be the first-best for the buyer side. This corresponds to a situation where producers are perfectly competitive and investment is chosen to maximize $W(s_t)$ only. Competitive sellers rationally foresee when the buyer side is going to invest and based on this, they choose a constant supply path to equalize prices across periods before and after the investment. In this setting, we can think that the choice is not only the overall period of resource use, $T+k$, but also a supply path q_t that maximizes consumer's welfare (2). We can copy the template from the social optimum to show that along consumers' first-best a optimal path, welfare $W(.)$ is linear, that is, $W(s_0) = \lambda s_0$ for some constant λ. In figure 1, we can maximize the buyer's value of the resource if we find the supply level q^* on the curve of utility surplus $u(q)$ where the line through $(0, \overline{u})$ and $(q, u(q))$ has the steepest slope over its domain $[0, q^m]$, where restrict the domain without loss of generality. We take restriction q^m to be the static monopoly supply, $q^m = \arg\max \pi(q)$, because this allows us to use it as a point of reference in the strategic equilibrium. Obviously, the restriction must satisfy $\bar{u} < u(q^m)$, otherwise the resource could not provide surplus above the long-run level.

If surplus $u(q)$ is convex, the slope is steepest at the maximum supply level: the buyers' optimal resource supply is given by $q^* = q^m = \arg\max u(q)$. For the general case, we search for the steepest line through $(0, \overline{u})$ and $(q, u(q))$. If the optimal level $q^* < q^m$, then q^* must satisfy

$$u(q^*) = \overline{u} + q^* u'(q^*). \tag{5}$$

As q^* determines the date of investment, by $T + k = s_0/q^*$, we have a simple graphical determination of the consumers' optimum. Relative to the social optimum, consumers can increase their payoff by forcing sellers to sell the resource faster:

Proposition 2 *The resource supply in the buyers' optimum exceeds resource supply in social optimum: $q^* > q^{**}$, and the period of resource dependence is shortened.*

Proof. We consider the two cases: first when $q^* = q^m$ and then when $q^* < q^m$. If $q^* = q^m$, then by assumption $u(q^*) > \overline{u}$, and since $u(q)$ is strictly increasing ($u' = -q\widetilde{u}'' > 0$), it follows that $q^* > q^{**}$. If $q^* < q^m$, then it does not follow directly by assumption, but from (5) and $u' > 0$, it follows that $u(q^*) > \overline{u}$, and thus $q^* > q^{**}$. ■

The opposing interests are now clear: the seller side would like to delay investment as much as possible (to spread supplies thinly over time), and the buyer side prefers faster depletion.[11] It is obvious that in the equilibrium of the game supplies and investment time must lie between the extremes identified here.

For future reference, we define the buyer's marginal value of the resource as $\lambda^* = [u(q^*) - \overline{u}]/q^*$. In the buyer's optimum, the consumers' share in total resource surplus $V(s_0) + W(s_0)$ is $\lambda^* s_0$; the sellers receive the remainder.

3 Strategic resource dependence

There are three types of agents in the model. First, producers of the resource form a coherent cartel (from now on, the seller). Second, large number of competitive consumers derive utility from resource consumption or, if present, from consuming the substitute service provided by the substitute. Third, there is the consumers' agent who cares only about the consumer surplus. The buyers' agent can affect the surplus only by making the decision to end the relationship with the seller. The decision is about changing the demand infrastructure which requires coordinated action on the buyer side but we abstract from the policy instrument implementing the change. In short, we interpreted the decision as investment in substitute technologies. Since the only strategic actions are taken by the seller and the buyer's agent, from now on we use the words 'buyers' agent' and 'buyer' interchangeably. There is one single market: the spot market for the resource flow.

3.1 Timing and strategies

The economy has three stages, starting in initial stage before investment, $t < T$, labeled with superscript '0'. The next stage follows investment, $T \leq t < T + k$, also called the post-investment stage, or labeled with superscript '1'. The final stage is after arrival of the new substitute technology, $t \geq T + k$. During the pre-investment stage, buyer and seller can interact strategically, where the seller chooses a supply level q^0, and the buyer decides whether or not to invest, $d \in \{0, 1\}$. Since the investment decision is irreversible, the game moves to the investment stage permanently once the buyer invests. During

[11] These results are consistent with the common view that the seller's market power makes the resource-depletion path more conservative (see Hotelling 1931). Buyers' market power speeds up consumption both in the optimal tariff literature (see Karp-Newbery 1993) and strategic R&D and technology literature (see the papers cited in the introduction).

the post-investment stage, there are no strategic interactions. The seller can only sell the remaining stock in k periods (or the monopoly quantity q^m if the stock is too large to be sold in this time span), and the buyer side can only accept what is offered to the market.[12] We denote the quantity sold in period t in the second stage by q_t^1. In the final stage, all resources remaining at time $T+k$ are left unused.

All strategic interaction thus takes place before investment. At any period t, if the game is in the pre-investment stage, we denote the seller's supply by q_t^0 and assume that there are three sub-stages with the following actions:

1. Seller chooses a supply q_t^0;

2. Buyers' agent chooses $d_t \in \{0, 1\}$;

3. If $d_t = 0$, market clears at q_t^0. If $d_t = 1$, the economy moves to the second stage.

We are interested in Markov-perfect strategies and look for seller strategies that are functions of the form $q_t^0 = \eta(s_t)$. Similarly, strategies of the buyers' agent are functions of the stock and the supply offer $d_t = \mu(s_t, q_t^0) \in \{0, 1\}$.

3.2 Buyers' problem

When buyers have taken the action to move to the substitute, the game is over: buyers have no more decisions to make and the seller can only sell the remaining stock during the transition period. When not yet used, the buyers' strategic investment option will affect the supply levels. To describe the buyers' payoff, we need to make it contingent on whether the strategic variable has been used or not. We define $W^I(s_t)$ as the value of the excursion above the long-run payoff measured again from current period t onwards, immediately after investment when resource dependence still continues for k periods. $W^I(s_t)$ is unambiguously determined by the seller's post-investment supply policy which is just $q_t^1 = \min\{q^m, s_t/k\}$ for the remaining sales window.[13] If buyers' decision is made at some T with $s_T > 0$, then

[12] For simplicity, we assumet that the buyers' agent has no other instruments to influence the seller's behaviour than the investment decision.

[13] Recall that profit $\pi(q)$ is concave so it is optimal to allocate the remaining stock evenly, or leave some stock left if this would imply exceeding the monopoly quantity q^m. In the presence of discounting, the sales path is flat, but declining as in Hotelling (1931). However, it still holds that all strategic interactions end at the investment date. We cover this case in Section 4.

$$W^I(s_T) = \begin{cases} k(u(s_t/k) - \bar{u}) \text{ if } s_T < kq^m \\ k(u(q^m) - \bar{u}) \text{ otherwise,} \end{cases} \tag{6}$$

It follows that for $s_T < kq^m$ we have $W^{I\prime}(s_T) = u'(s_T/k)$, which measures the scarcity cost to the buyer from continued resource dependence.

Taking together the two periods before and post-investment, welfare (2) becomes

$$W(s_0) = \int_0^T [u(q_t) - \overline{u}]dt + W^I(s_T) \tag{7}$$

We assume that the seller has a strategy $q_t^0 = \eta(s_t)$, and based on the seller's strategy we find the strategy for the buyer to invest. The dynamics are best understood when we consider supply constant over a small period $[t, t+\varepsilon]$, and let ε converge to zero. Using the above expression for $W^I(s_t)$ and assuming the seller's strategy $q_t^0 = \eta(s_t)$, we can write the expression for the payoff before the investment, $W(s_t)$, when the buyer optimizes over a short period length ε:

$$W(s_t) = \max_{d_t \in \{0,1\}} \{[\varepsilon u(\eta(s_t)) - \varepsilon\bar{u} + W(s_t - \varepsilon\eta(s_t))](1 - d_t) + W^I(s_t)d_t\}. \tag{8}$$

Term $\varepsilon\bar{u}$ is the direct cost from postponing the investment since the buyer side loses long-run surplus $\bar{u}$ for ε units of time by not investing today. As ε approaches zero, (8) can be approximated as follows:

$$W(s_t) = \max_{d_t \in \{0,1\}} \{[\varepsilon u_t^0 - \varepsilon\bar{u} - \varepsilon q_t^0 W'(s_t) + W(s_t)](1 - d) + W^I(s_t)d\}, \tag{9a}$$

where we use shorthands $u_t^0 = u(\eta(s_t))$ and $q_t^0 = \eta(s_t)$. Thus, if choosing $d = 0$ is optimal, then $W(s_t) \geq W^I(s_t)$ and

$$u_t^0 = \bar{u} + q_t^0 W'(s_t). \tag{10}$$

This is the key indifference throughout this paper. It says that the consumer surplus under continuation of the resource dependence, u_t^0, covers the direct cost from continuing, $\bar{u}$, and the marginal reduction in payoff from the fact that the stock available for consumption during remaining overall period of resource dependence is depleted, $q_t^0 W'(s_t)$. Notably, this condition closely resembles the buyer's optimum (5) if welfare functions before $W(.)$ and after investment $W^I(.)$ coincide. There is one important distinction. Whereas the right-hand-side of the buyer's optimum indifference condition (5) takes the constant marginal value of the resource at the buyer's optimal path and so defines a constant q^*, the strategic buyer's indifference condition (10) is based on the marginal value of the current resource and so it defines a supply scheme q_t^0 that is dependent on the current resource level s_t.

3.3 Seller's problem

Let $V^I(s_T)$ denote the seller's payoff if buyers make their decision to end the relationship at stock level s_T. This value is simply given by

$$V^I(s_T) = \begin{cases} k\pi(s_t/k) \text{ if } s_T < kq^m \\ k\pi(q^m) \text{ otherwise.} \end{cases} \tag{11}$$

Let us then consider the seller's problem before the decision is made. Let $V(s_t)$ denote the value of the remaining stock to the seller conditional on no investment before t. For short period ε, and given the buyers' strategy $d_t = \mu(s_t, q_t^0)$, supply in the next ε periods is q_t^0 if $\mu(s_t, q_t^0) = 0$. The economy immediately moves to the investment stage if $\mu(s_t, q_t^0) = 1$. The seller's best response satisfies

$$V(s_t) = \max_{\{q_t^0\}}\{[\varepsilon\pi(q_t^0) + V(s_t - \varepsilon q_t^0)](1 - \mu(s_t, q_t^0)) + V^I(s_t)\mu(s_t, q_t^0). \tag{12}$$

When ε approaches zero, this value can be approximated by (letting $\mu(\cdot) = \mu(s_t, q_t^0)$):

$$V(s_t) = \max_{\{q_t^0\}}\{[\varepsilon\pi(q_t^0) - \varepsilon q_t^0 V'(s_t) + V(s_t)](1 - \mu(\cdot)) + V^I(s_t)\mu(\cdot)\} \tag{13}$$

Given $\mu(s_t, q_t^0)$, the seller can choose if there will be investment or not. If choice $\mu = 0$ is implemented, then by (13), we must have

$$-q_t^0 V'(s_t) + \pi(q_t^0) = 0. \tag{14}$$

If choice $\mu = 1$ is implemented, then

$$V(s_t) = V^I(s_t). \tag{15}$$

From these conditions we can immediately see that the seller always prefers to continue the relationship. Let $q_t^0 \leq s_t/k$, then

$$V'(s_t) = \psi(q_t^0) \geq \psi(\frac{s_t}{k}) > \psi(\frac{s_t}{k}) + \frac{s_t}{k}\psi'(\frac{s_t}{k}) \geq V^{I\prime}(s_t).$$

The first equality follows from (14), the second weak inequality is by assumption, the third strict inequality follows from a negative price slope, and the last weak inequality follows from (11). Thus, the 'smooth pasting' condition does not hold for V for the seller. Let s^* be the stock level at which investment takes place, than $V'(s^*) > V^{I\prime}(s^*)$, and the inequality extends to all larger stock levels. Buyers decision implies a binding time-to-sell constraint for the seller; the seller will never end the dependence before the buyer wants to end it, as it is always profitable to extend the sales period beyond $T + k$

when discounting is absent.[14] For this reason, when the stock level is public knowledge and $q_t^0 \leq s_t/k$ - the seller has no reason to supply more before investment when compared to the supplies after investment - it will be the buyers' indifference that determines the time to end the resource dependency.

Lemma 2 *If for all $s_t > s^*$, $q_t^0 \leq s_t/k$, then the seller prefers continuation to stopping for all $s_t > s^*$, $V(s_t) > V^I(s_t)$.*

As we will see below, with publicly observed stock levels s_t, the condition $q_t^0 \leq s_t/k$ always holds.[15]

The value $V^I(s_t)$ is depicted in Fig. 2 as a solid line for stock levels below s^*, describing the post-investment stage, where this value is the actual value of the stock, and then as a dotted line for stocks above s^*, where this value only acts as an opportunity value. Sales strategy prior to investment, $q_t^0 = \eta(s_t)$, has to be solved together with the buyers' strategy, and we turn next to this.[16]

3.4 Equilibrium

Establishing and characterizing equilibrium supply is a simple undertaking based on the analysis of buyers' indifference between continuation and stopping, given that the seller side never prefers stopping. We first prove that (6) defines the buyer's welfare any time before investment:

Lemma 3 *In equilibrium, the buyer is indifferent between continuing the resource dependence and investing at any given t prior to the investment date:*

$$W(s_t) = W^I(s_t) \text{ for all } s_t \geq s^* \tag{16}$$

Proof. The proof is by contradiction. Assume $W(s_t) > W^I(s_t)$ at some $s_t > s^*$. The inequality implies that the buyer will always choose $d_t = 0$ in (8), irrespective of

[14] We will derive this same condition also with discounting but there we need restrictions on the utility formulation.

[15] However, when stock levels are unobserved, we will see that the condition can break down: the seller may supply more before investment as compared to supply after investment. Such a strategy can be used to make the buyer to believe that the stock is larger than it actually is.

[16] If the equilibrium value function $V(s)$ is convex for $s \geq s^*$, supplies increase as the stock is depleted; for a concave $V(s)$, the opposite holds. We will show, after studying the equilibrium in general, that $V(s)$ is convex when s is close to the investment level s^*; convexity of $V(s)$ holds for all stock levels if $u(.)$ is concave.

the seller's supply. In turn, the seller is not constrained to reduce supplies and he can extend the period of resource dependence to obtain higher prices from all periods. Supply will fall arbitrarily close to zero, the utility excursion compared to $\bar{u}$ becomes negative for a period of unbounded length, and $W(s_t)$ becomes negative (2), which contradicts $W(s_t) > W^I(s_t)$. ■

It is thus the buyers' indifference that determines equilibrium supply policy, $q_t^0 = \eta(s_t)$. The buyer's indifference condition (16) together with (10) requires

$$u(q_t^0) - \bar{u} - q_t^0 u'(s_t/k) = 0 \text{ if } s_t < kq^m \quad (17)$$

$$u(q_t^0) - \bar{u} = 0 \text{ otherwise,} \quad (18)$$

because $W_t'(s_t) = u'(s_t/k)$ when $s_t < kq^m$, and $W_t'(s_t) = 0$ otherwise as the stock level does not affect supply if $s_t > kq^m$. To illustrate, assume a concave surplus u and see Fig. 3. The slope of $u(q)$ at s_t/k determines the scarcity cost of continuation. A line with this slope and intercept $\bar{u}$, the waiting cost of the substitute, intersects with $u(q)$ at the equilibrium supply level. As the stock is depleted, the increase in the slope of $u(q)$ at s_t/k reflects the increasing scarcity and the equilibrium supply q_t^0 compensating the buyers must increase. There exists s^* such that the line $\bar{u} + q_t^0 u'(s^*/k)$ is tangent to $u(q)$ (as in Fig 1). At this point, $q_t^0 = s^*/k$. Note that this supply equals q^*, the buyers' first-best supply as it maximizes the buyers' average payoff from this stock level onwards. The seller cannot compensate the buyer for continuation after the stock has fallen below s^* because the buyer can implement his first-best by ending the relationship there. Alternatively put,

$$W'(s_t) > \lambda^* = [u(q^*) - \overline{u}]/q^* \text{ for } s < s^*.$$

For the general case, it is important to distinguish two cases. First, we say that the buyer has a *strong substitute* if the buyers' optimum requires more supply than the static monopoly supply. Because of the restriction on domain, a strong substitute implies $q^* = q^m$. Recall that a larger q^* follows from a larger long-run surplus $\bar{u}$ as the buyer wants to consume the resource faster the better the outside option (the lower is c). Second, we say that buyer has a *weak substitute* if $q^* < q^m$. Equilibrium under strong substitute is described in the first proposition below. When the substitute is weak, buyer's continuation considerations depend more on the stock dynamics, i.e., how much there is left of the stock for the transition period. Equilibrium under weak substitute is described in the second proposition below.

Proposition 3 *If the buyer has a strong substitute ($q^* = q^m$), there exists a unique Markov-perfect equilibrium. The investment stock and supply path satisfy $s^* = kq^m$, $q_t^0 = u^{-1}(\bar{u})$, $q_t^1 = q^m$. The consumers only share in total resource surplus after investment, $W(s_0) = \lambda^* s^*$.*

Proof. The supply levels follows immediately from (17)-(18) if we can show that $s^* = kq^m$. For all $s_t \geq kq^m$, buyer has no reason to invest when the seller offers $q_t^0 = u^{-1}(\bar{u})$, and the seller does not want to trigger investment by supplying less. We are left to prove that $s^* < kq^m$ is impossible. By the fact that $q^* = q^m$ gives the highest surplus,

$$u(q) \leq \overline{u} + \frac{u(q^m) - \overline{u}}{q^m} q \ , \ \forall q \leq q^m.$$

On the other hand, if $s^* < kq^m$, then (17) must hold for all $s^* < s_t < kq^m$. But this implies that exists small $\varepsilon > 0$ such that

$$u'(s_t/k) > \frac{u(q^m) - \overline{u}}{q^m}$$

for all s_t in $q^m - \varepsilon < s_t/k < q^m$. Combining,

$$qu'(s_t/k) > q\frac{u(q^m) - \overline{u}}{q^m} \geq u(q) - \overline{u}$$

for all $q \leq q^m$, which is the contradiction. Thus, we must have $s^* = kq^m$. ■

We are now left with the more interesting case of weak substitute ($q^* < q^m$). Recall that the buyers' first-best supply q^* satisfies

$$u(q^*) = \bar{u} + q^* u'(q^*)$$

and that buyers' never accept stock levels below kq^*: buyers can always implement their first-best by ending the relationship at $s_t = kq^*$. It thus clear that only if $s^* \geq kq^*$, (17) can be satisfied. This way q^* defines the lowest stock level where investment takes place. However, since the consumer surplus is not generally concave, buyers may also end the relationship at some higher stock level $s^* > kq^*$, because the scarcity cost $u'(s/k)$ may locally increase above $u'(q^*)$ as s/k declines from s_0/k towards q^*. To deal with this, we define s^* to be the first stock level below s_0 such that $u'(s^*/k) = u'(q^*)$. Stock s^* is unique for given s_0, and we have

$$u'(s_t/k) < u'(q^*)$$

for all $s^* < s_t \leq kq^m$. By continuity, $q_t^0 = \eta(s_t)$ must vary with the remaining stock for $s^* < s_t < kq^m$ to keep the buyer indifferent between stopping and continuing.

Proposition 4 *If the buyer has a weak substitute ($q^* < q^m$), there exists a unique Markov-perfect equilibrium with s^* as defined above, q_t^0 defined by (17)-(18), and $q_t^1 = s^*/k$.*

Proof. As in the previous proposition, it suffices to prove that s^* is determined properly. Clearly, we cannot take s^* to be smaller as such would imply an infeasible resource supply from (17). We will now prove that s^* cannot be larger either. For this, it is sufficient to prove that s^* maximizes the value of the resource to the seller. But this follows from Lemma 2: the seller maximizes profits by continuing as long as possible. ■

These results suggest an interesting limiting case. Recall that q^m is defined by demand only but $\bar{u}$ depends also on c. By varying c we can choose the socially optimal supply such that $q^{**} = u^{-1}(\bar{u}) = q^m$, implying, by Proposition 3, that the equilibrium coincides with the first-best. Making the substitute weaker delays consumption both in the social optimum and in the equilibrium, but more in the latter. Thus, we have

Proposition 5 *In a strategic equilibrium, resource consumption exceeds the socially optimal level, and falls short of the buyer's first-best level.*

We find the case of a weak substitute most relevant and use next the equilibrium conditions to characterize equilibrium supply path. When the remaining stock is larger than kq^m, adoption of the substitute technology today would imply that some stock is left over due to the fact the seller does not prefer to exceed the monopoly quantity during the technology transition period. Therefore, to keep the buyer side willing to continue, the seller only needs to compensate the loss from postponing the arrival of the long-run surplus, $u(q_t^0) - \bar{u} = 0$ (see 18), leading to an initially flat supply path. As s_t falls below kq^m, continuation increases scarcity since the stock available for consumption during the technology transition period is depleted, which increases the buyer's cost from continuing resource dependence and thus commands a larger compensation. This compensation is measured by $q_t^0 u'(\frac{s_t}{k})$ in (17), which jumps to a positive value at $s_t = kq^m$. In case of concave surplus $u(q)$, supply increases as s_t declines below kq^m until reaching $s = s^*$, after which the supply path is flat again but now at level s^*/k. Under nonconcave surplus, the increase in supply may not be monotonic as the buyer's scarcity cost may vary. However, when the equilibrium path approaches the investment point, supplies must increase, so that our main conclusion holds irrespective of the utility functional form.

Proposition 6 *Under weak substitute, the equilibrium supply path q_t is*

1. *constant at level* $u^{-1}(\bar{u})$ *when* $s_t > kq^m$;

2. *varying over time in* $u^{-1}(\bar{u}) \leq q_t \leq q^*$ *when* $s^* < s_t < kq^m$, *but ultimately increasing to* q^* *as* s_t *approaches* s^*;

3. *strictly increasing for all* $s^* < s_t < kq^m$ *if consumer surplus* $u(q)$ *is concave*

We have depicted a supply path in Fig. 4, where we also show the buyers' optimal supply path as a flat line at level s^*/k.

4 Unobserved reserves

The size of the remaining stock is what determines the seller's ability to entice the buyer side to postpone actions ending the resource dependence. In the above strategic equilibrium, it is obviously critical that the buyer side can observe how much resource there is left, otherwise the seller might take advantage of the buyers' imperfect information for the right timing of the infrastructure change. To see how the seller might distort the buyer's investment decision, see Fig. 4 again and note that the larger is the seller's stock, the lower is the equilibrium supply (earlier points on the sales path are associated with larger stocks). In this precise sense, a large stock implies more market power than a small stock. If the stock is not observed by the buyer side, a small seller can potentially mimic the large seller's policy of reducing supplies and thereby extend the investment period from what would hold for the small seller under perfect observability.

To extend the model to cover this situation, we assume that the privately observed initial stock can take values from an interval $[s_0^L, s_0^H]$, where the distribution is uniform. The range of different seller types is identified with label i, so that we write for the initial reserve, s_0^i, and thus the seller's behavioral strategy maps from the history of the game and type, (h_t, s_0^i), to current sales q_t^i. The buyer still observes q_t in addition to history h_t before making the investment choice, $d_t \in \{0, 1\}$, but has only beliefs on the seller type s_0^i. Cumulative past sales Q_t will be the history, $h_t = Q_t$, as this will be sufficient for updating of beliefs in the equilibrium that we discuss.

To set up the framework, let us assume that all remaining seller types have a strategy that asks them to supply the same quantity $q_t^p = \eta(Q_t, s_0^i)$ after a given history Q_t. We proceed by determining how large q_t^p needs to be to entice the buyer side to continue, and how the buyer rationally infers what seller types find it individually optimal to follow this strategy. Note first that the buyer can force information revelation by investing:

it is individually rational for all i to choose $q^i = [s_0^i - Q_t]/k$ in the post-investment phase, so that the underlying stock can be inferred from the supply.[17] Consider then the buyer's payoff immediately after investment, given a uniform posterior of possible remaining stock levels $[s_t^L, s_t^H]$,

$$W^I(Q_t) = \theta_t^{-1} \int_{s_t^L}^{s_t^H} ku(s_t^i/k) ds_t^i - k\bar{u}, \tag{19}$$

where $\theta_t = s_t^H - s_t^L$.[18] We describe shortly how posterior $\theta_t = s_t^H - s_t^L$ is updated, using sellers' individual rationality, but is should be clear that the investment payoff $W^I(Q_t)$ depends on Q_t as it determines how the potential initial stock levels have changed. Given the knowledge of $W^I(Q_t)$ and the observed $q_t^p = \eta(Q_t, s_0^i)$, it is straightforward to define the buyer's payoff from not investing using the same procedures as in the deterministic case. This payoff depends now on the cumulative sales and is denoted by $W(Q_t)$.[19] Note that $W'(Q_t) < 0$ as Q_t is cumulative sales rather than the remaining stock. For a short period length, if the buyer is just indifferent between continuing and stopping, we must have $W(Q_t) = W^I(Q_t)$ and

$$u(q_t^p) = \bar{u} - q_t^p W^{I\prime}(Q_t) \tag{20}$$

where the right-hand side is the opportunity cost of the continued resource dependence. Given the uniform posterior, we have a closed-form expression for $W^{I\prime}(Q_t)$:[20]

$$W^{I\prime}(Q_t) = \theta_t^{-1}[u(s_t^L/k) - u(s_t^H/k)]. \tag{21}$$

Substitution of (21) in (20) gives the equivalent of (17)-(18):[21]

$$u(q_t^p) = \bar{u} + q_t^p \theta_t^{-1}[u(s_t^H/k) - u(s_t^L/k)] \tag{22}$$

This equation simply determines the minimum level of supply that the sellers have to provide not to trigger investment, given the beliefs on the lower and upper bound for the

[17] No type will choose $q^i > q^m$, as in the deterministic case but, for convenience, we will not keep track of this condition as it has no material affect on the equilibrium.

[18] For ease of exposition and without loss of generality, we leave out the possibility that $kq^m < s_t^i$ for some seller types. The formulation including this option is $W^I(Q_t) = \int_{\tilde{s}_t}^{s_t^H} \theta_t ku(\min\{q^m, s_t^i/k\}) ds_t^i - k\bar{u}$.

[19] Formally, we define the game in discrete time as previously but characterize the equilibrium conditions for a very short period length. Given the observed $q_t^p = \eta(Q_t, s_0^i)$, the buyer's value function over a short period of time satifies $W(Q_t) = \max_{d_t \in \{0,1\}}\{[\varepsilon u(q_t^p)) - \varepsilon\bar{u} + W(s_t + \varepsilon q_t^p)](1 - d_t) + W^I(Q_t)d_t\}$.

[20] The precise RHS is $\theta_t[u(\min\{q^m, s_t^L/k\}) - u(\min\{q^m, s_t^H/k\})]$.

[21] Notice that under perfect observability we had two conditions dependent on whether $s_t/k > q^m$, or not (see (17)-(18)). Here, we do not need to make this distinction, but when written out full, in the above formula one should read $\min\{u(q^m), u(s_t^H/k)\}$ and $\min\{u(q^m), u(s_t^L/k)\}$, rather than $u(s_t^H/k)$ and $u(s_t^L/k)$, respectively.

stock size s_t^L and s_t^H. Note the close analog of (17) and (22): we must have $-W^{I\prime}(Q^*) = W^{I\prime}(s^*)$ and thus $\eta(Q^*, s_0^i) = q^*$ at the investment point, where Q^* is the cumulative sale that triggers investment. Thus, if the seller type remains unobserved at the investment point, quantity supplied q^* is exactly the same when triggering investment under perfect information. In a similar fashion as in the deterministic case, when $W^{I\prime}(Q_t) > \lambda^*$ there is no supply q_t^p that satisfies the buyer's indifference condition. The buyer thus always invests when

$$u(s_t^H/k) - u(s_t^L/k) \geq \theta_t \lambda^*. \tag{23}$$

We are now ready to explain and prove our conjecture for an equilibrium. When $\theta_0 \to 0$, the initial stock becomes precisely known and the buyer's indifference condition coincides with the perfect information analog. It seems therefore reasonable to think that for small θ_0, the equilibrium is not that different from the perfect information equilibrium where the one seller type prefers to supply until the buyer's indifference breaks down. Similarly, when θ_0 is small, all potential seller types find it individually rational to follow $q_t^p = \eta(Q_t, s_0^i)$, given the buyer's beliefs that we will specify shortly, until $Q_t = Q^*$ and $\eta(Q_t^*, s_0^i) = q^*$. In such an equilibrium, all private information is revealed by the buyer's action at the investment point but not before. This equilibrium has two main properties: (i) timing of investment is public information (determined by buyer whose beliefs are publicly known); and (ii) no supply shocks take place before the investment.

When θ_0 is sufficiently large, the above conjecture cannot be an equilibrium: when there are sufficiently small sellers in the distribution of types, they will run out of the stock before the buyer's indifference condition (22) breaks down. These stock owners prefer to trigger investment earlier, that is, before they have run out of stock. This equilibrium has the following main properties: (i) timing of investment is private information (determined by seller whose type is privately known); and (ii) there is a persistent possibility of a supply shock during the period of strategic resource dependence. We call the equilibrium with these properties risky.

Whether the equilibrium is risky or not depends on the riskiness of the underlying seller type distribution. There will be a cutoff value, which we denote by θ^*, such that when $\theta \leq \theta^*$, the equilibrium is nonrisky, and when $\theta > \theta^*$, it will be risky. To determine this cutoff, we need to find out the marginal seller type for which it is individually rational to follow the pooling strategy $q_t^p = \eta(Q_t, s_0^i)$ until the buyer invests. To this end, we work backwards in time, from time T when the buyer invests and (23) is satisfied. For all periods $t < T$, the buyer indifference determines the supply level q_t^p required to prevent investment, and the seller, which is of type i, determines whether he will supply

q_t^p, or alternatively, whether he can gain from revealing his identity i (by supplying less than $q_t^p = \eta(Q_t, s_0^i)$ and thus breaking the buyer's indifference). We can write the payoff for seller type i if it triggers investment today after sales history Q_t as:

$$V^I(Q_t, s_0^i) = k\pi(\frac{s_0^i - Q_t}{k}). \tag{24}$$

Seller of type i chooses to supply $q_t^p = \eta(Q_t, s_0^i)$ to make the buyer to continue if $V(Q_t, s_0^i) \geq V^I(Q_t, s_0^i)$. Under continuation, the first-order conditions imply

$$q_t^p V_Q(Q_t, s_0^i) + \pi(q_t^p) = 0 \tag{25}$$

which is analogous to condition (14) in the perfect information case. At the time of investment, $V(Q_t, s_0^i) = V^I(Q_t, s_0^i)$ for all sellers i that have not triggered investment before T. A very short period ε before investment T, we have that $V \geq V^I$ if and only if

$$\pi'(s_t^i/k) \leq \frac{\pi(q_t^p)}{q_t^p}. \tag{26}$$

So let us define the marginal continuing type $s^{\min}$, at the time the buyer invests, by

$$\pi'(s^{\min}/k) = \frac{\pi(q^*)}{q^*}. \tag{27}$$

If $s_T^L \geq s^{\min}$, then it follows that (26) is satisfied for all $s_t^i \geq s_t^L$, and when q_t^p decreases going back in time from T, and s_t^L increases, (26) will be satisfied for all $t \leq T$.[22] By integration, we have $V(Q_t, s_0^i) > V^I(Q_t, s_0^i)$ for all t. On the other hand, if $s_T^L < s^{\min}$, then by integration over $[t, T]$ where t is shortly before T we have $V(Q_t, s_0^L) < V^I(Q_t, s_0^L)$. In this case, the seller type L would rather trigger investment at $t < T$. Thus $s_T^L \geq s^{\min}$ is a necessary and sufficient condition to define a non-risky distribution. At period T, the high-stock level s_T^H is, in turn, derived from (23). From the value of $s_T^L = s^{\min}$ and the associated value of s_T^H, we can determine the maximum spread θ^* that is not risky, searching for the minimum value of θ for which the following equation holds:

$$u(s^{\min}/k + \theta/k) - u(s^{\min}/k) = \theta\lambda^*. \tag{28}$$

We can now graphically demonstrate how the risky distribution is determined. In Fig. 5 we show, in (s^L, s^H)-space, buyer's and seller's indifference curves, $I^B$and I^S,

[22]Recall from the perfect information case that suplies need not monotonically increase along the equilibrium path if u is not concave. The same obviously holds here. However, q^* is the highest possible supply level before investment.

respectively. A given I^B traces stock levels that keep the buyer indifferent as defined by (22) for a given supply q_t; lower indifference curves are associated with higher supply. It is instructive to start from the 45-degree line where $\theta = 0$ and so the underlying supply equals the perfect information equilibrium level. The perfect information equilibrium progresses along this line, e.g., from C to A such that at A the buyer's indifference breaks down. Point A thus corresponds to stock levels (s^*, s^*) and supply level q^*. Consider a small informational asymmetry, for example, such that prior $\theta_0 > 0$ puts point D as a starting point. Then, if the equilibrium is nonrisky, it moves from D to B where supply is again q^* (B is on the same indifference curve as A). However, point B is critical as also the seller's indifference curve I^S passes through B. Curve I^S is defined jointly by (22) and

$$q_t^p \pi'(s_t^L/k) = \pi(q_t^p), \tag{29}$$

so that I^S gives for each supply level q_t^p the marginal continuing seller type. Note that for higher supply levels (lower I^B), the marginal type is higher (I^S slopes downwards), and that the type at B is $s_0^i = s^{\min}$. The horizontal difference between lines CA and DB is thus the critical θ^*. For any $\theta \leq \theta^*$, equilibrium starts from point between the two lines and is nonrisky: investment date is determined by the buyer and this is public information. For any $\theta > \theta^*$, equilibrium is risky. Consider, e.g., point E where the informational asymmetry is so large that small seller types find it individually rational to trigger investment before the buyer's lowest indifference curve passing through A and B is reached. Then, the equilibrium first progresses from E to F where (29) becomes binding for the smallest sellers in the distribution. From this point onwards, it moves along I^S so that the buyer revises the posterior θ_t after each period of no supply shock by ruling out seller types that should have triggered the shock by t. The posterior becomes more precise, conditional on no shock, until reaching θ^* at B where the buyer invests.

Proposition 7 *If $s_0^H - s_0^L \leq \theta^*$ ($> \theta^*$), a nonrisky (risky) equilibrium with the above properties exists.*

Proof. See above for the construction of θ^* and equilibrium beliefs. Fig. 5 assumes nice curvature properties for the indifference curves that follow, for example, when u is concave. However, nothing in the construction of equilibrium beliefs requires concavity (general version of Fig. 5 is available on request).

We consider now out of equilibrium beliefs that support the conjectured equilibrium outcome. There are two cases to consider: at each t, the seller may offer $q_t > q_t^p$ or

$q_t < q_t^p$. If $q_t > q_t^p$, any belief will do. The buyer can become more optimistic relative to the equilibrium belief about the stock size on observing $q_t > q_t^p$ (strictly prefers continuation to investment). The buyer can become more pessimistic about the stock size when observing $q_t > q_t^p$. Depending on q_t and on the explicit formulation of the beliefs, the buyer may or may not invest. In all cases, no seller type gains from deviating from the equilibrium to this outcome.

Conditional on observing $q_t < q_t^p$, the buyer's belief about the stock size must become more pessimistic relative to equilibrium beliefs. If the buyer became more optimistic and would not invest, then all sellers have reason to supply less. More optimistic beliefs after observing $q_t < q_t^p$ are thus inconsistent. Supplying $q_t < q_t^p$ will automatically trigger more pessimistic beliefs and investment. Given this, no seller prefers to deviate from the equilibrium. ■

In Fig. 6 we show a time path for supply in a risky equilibrium. Similar as to the perfect information case, concavity of u ensures that supplies are increasing throughout the equilibrium (conditional on no shock), although supplies must ultimately increase for any u. Initially, there can be a supply period with zero probability of a supply shock (corresponding to EF in Fig. 5) but ultimately small sellers can be ruled out only by observing no supply shock (FB in Fig. 5). Two such small seller types with their deviations are depicted in Figure 6.

5 Discounting

Discounting is obviously an important element in resource use when the relevant time horizon is at least decades. In the traditional Hotelling model, discounting is what makes markets in different periods to differ, which, in the presence of market power, leads to intertemporal price discrimination. Discounting is thus one reason to discriminate buyers in different periods. Another reason is the buyers' changing opportunity cost of continuing the resource dependence due to stock depletion, which we have identified in the undiscounted analysis. The purpose of this section is to explain how these two distinct reasons for price discrimination evolve as the stock depletion progresses. The main case that we want to emphasize is the one where supplies initially decline, when the stock is large, as in a traditional Hotelling exhaustible resource market. However, ultimately supplies must increase, when stock declines and the buyers' outside option starts to drive the equilibrium dynamics as in the undiscounted case.

We focus on the full information case here. First, we explain how the payoff expressions and the relevant indifference conditions prior to investment extend to the discounted case. It becomes clear that the equilibrium implied by these conditions converge to the undiscounted limit we solved already. Second, we extend the previous method of using the buyers' indifference for finding the investment time, and we solve the equilibrium for the constant relative risk aversion formulation (CRRA).

Let discounting be positive, $r > 0$. In the post-investment phase, the equilibrium does not change much: for the seller, there is a unique profit-maximizing supply path, equalizing present-value marginal revenues over the remaining sales period, and resulting in an associated value function $V^I(s_T)$ at the time of investment.

In the pre-investment period, equation (12) determining the seller's strategy $q_t^0 = \eta(s_t)$ becomes

$$V(s_t) = \max_{\{q_t^0\}}\{[\varepsilon\pi(q_t^0) + e^{-\epsilon r}V(s_t - \varepsilon q_t^0)](1-\mu(s_t, q_t^0)) + V^I(s_t)\mu(s_t, q_t^0)\}. \tag{30}$$

For a short time period ε, value function $V(s_t)$ satisfies

$$-q_t^0 V'(s_t) + \pi(q_t^0) - rV(s_t) = 0. \tag{31}$$

The unique seller's supply path after investment also defines the buyers' welfare $W^I(s_T)$, where we note that since $W^I(s_T)$ measures only value of the excursion above the long-run situation where flow payoff $\bar{u}$ is achieved, the overall welfare at the investment time is equal to $W^I(s_T) + \bar{u}/r - I$. The buyers' payoff before investment is now given by

$$\begin{aligned} W(s_t) + \bar{u}/r - I \quad = \quad & \max_{d_t \in \{0,1\}}\{[\varepsilon u(\eta(s_t)) + e^{-\epsilon r}W(s_t - \varepsilon\eta(s_t)) + e^{-\epsilon r}\bar{u}/r - e^{-\epsilon r}I](1-d_t) \\ & + W^I(s_t)d_t\}. \end{aligned} \tag{32}$$

Letting ε converge to zero, we find the positive discounting equivalent of (10):

$$u_t^0 \geq \bar{u} - rI + rW^I(s_t) + q_t^0 W^{I\prime}(s_t). \tag{33}$$

When the buyer is indifferent between continuation and stopping, (33) holds as an equality with obvious interpretation: waiting cost of continuation is now $\bar{u} - rI$ and, in addition to the depletion effect $q_t^0 W^{I\prime}(s_t)$, buyers must receive return on the asset they are holding (investment option), $rW^I(s_t)$. Assuming that the buyers' indifference condition is uniformly continuous in (s_t, q_t^0), it is also continuously differentiable in r, and so it is clear that for $r \to 0$, the equilibrium uniformly converges to the zero-discounting equilibrium.

Thus, the zero-discounting equilibrium describes well the equilibrium features of a low-discount rate equilibrium.

We will now explain under what conditions we can still use the buyers' indifference in determining the investment point. We will argue that the seller would always prefer continuation above investment when the supply path is sufficiently smooth at the investment point. Such smoothness is ensured by CRRA utility.

Let q^I refer to optimal monopoly supply immediately after investment. With zero discounting, we had $u'(q^I) = W^{I\prime}(s^*)$ as q^I equals the consumption level throughout the post-investment phase until the substitute arrives. With positive discounting, this equation does not hold. Recall that under positive discounting, supply q_t after investment satisfies $\pi'(q_t) = e^{rt}\lambda$, for some $\lambda > 0$ (marginal revenues are equalized in present value). Thus, when the resource stock increases by small amount Δs, then supply changes Δq_t satisfy $\pi''(q_t)\Delta q_t = e^{rt}\Delta\lambda$, for some $\Delta\lambda$ such that $\int_T^{T+k} \Delta q_t dt = \Delta s$, that is, $\int_T^{T+k} \frac{e^{rt}}{\pi''(q_t)} dt = \Delta s/\Delta\lambda$. For notation, let us use $\mu_t = \frac{\pi'(q_t)}{u'(q_t)} = \frac{q\widetilde{u}''(q_t)}{\widetilde{u}'(q_t)} + 1$. The value of μ measures one minus the relative risk aversion.

$$\begin{aligned} W^{I\prime}(s^*) &= \frac{\Delta W^{I\prime}(s)}{\Delta s} = \frac{\int_T^{T+k} e^{-rt} u'(q_t)\Delta q_t dt}{\int_T^{T+k} \Delta q_t dt} = \frac{\int_T^{T+k} e^{-rt} \mu_t \pi'(q_t)\Delta q_t dt}{\int_T^{T+k} \Delta q_t dt} \\ &= \frac{\int_T^{T+k} \mu_t \Delta q_t dt}{\int_T^{T+k} \Delta q_t dt}\lambda = \frac{\int_T^{T+k} \mu_t \Delta q_t dt}{\int_T^{T+k} \mu_T \Delta q_t dt} u'(q^I). \end{aligned} \tag{34}$$

The difference between $W^{I\prime}(s^*)$ and $u'(q^I)$ is caused by the difference between the average value of μ_t over the post-investment period $[T, T+k]$, and its value at time T. It is clear that, for utility with constant relative risk aversion, $W^{I\prime}(s^*) = u'(q^I)$. If utility has decreasing relative risk aversion, relative risk aversion will increase with decreasing q_t, and μ_t will increase, so that $W^{I\prime}(s^*) \geqslant u'(q^I)$. Similarly, if utility has increasing relative risk aversion, $W^{I\prime}(s^*) \leqslant u'(q^I)$.

Furthermore, we will show that the seller's value function has a kink at the time of investment, $V'(s^*) > V^{I\prime}(s^*)$ when $W^{I\prime}(s^*) = u'(q^I)$, so the seller would always prefer continuation rather than stopping in such a situation. In this paragraph, changes in k, play a role in the argument, and so when convenient, we write the seller's payoff as a function of both the stock level and the period length k. That is, we write $V^I(s_t, k)$ and $V^I(s_t)$ interchangeably, and similarly $V_s^I(s_t, k)$ and $V^{I\prime}(s_t)$. Flow profits are concave by assumption, and supplies strictly positive at the end of the overall sales period, $q_{T+k} > 0$, so it is clear that the seller's value of the resource increases with the period length

k, $V_k^I(s_t,k)>0$. After investment, the value function satisfies the following Bellman equation

$$V^I(s^*,k)=\varepsilon\pi(q^I)+e^{-\epsilon r}V(s^*-\varepsilon q^I,k-\varepsilon). \tag{35}$$

Taking the limit for $\varepsilon\to 0$ (leaving k out of notation), we get

$$\pi(q^I)-rV^I(s^*)-q^IV_s^I(s^*)-V_k^I(s^*)=0. \tag{36}$$

Thus, $\pi(q^I)>rV^I(s^*)+q^IV^{I\prime}(s^*)$. This together with continuous supply implied by CRRA and value matching, $V(s^*)=V^I(s^*)$, implies $V'(s^*)>V^{I\prime}(s^*)$.

Now, we know that for CRRA utility, the equilibrium investment point is determined by the breakdown of the buyers' indifference condition. Let us see how this works and assume $\widetilde{u}(q)=q^\sigma$, so that $\psi(q)=\sigma q^{\sigma-1}$, $\pi(q)=\sigma q^\sigma$, and $u(q)=(1-\sigma)q^\sigma$. One can derive

$$\begin{aligned} V^I(s) &= \sigma A s^\sigma \\ W^I(s) &= (1-\sigma)As^\sigma-\frac{1-e^{-rk}}{r}\bar{u}, \end{aligned}$$

where $A=\left(\frac{\omega}{1-e^{-\omega k}}\right)^\sigma\left(\frac{1-e^{-\omega\sigma k}}{\omega\sigma}\right)$ and $\omega=\frac{r}{1-\sigma}$. Notice that $A\to k^{1-\sigma}$ for $r\to 0$ (as one should expect). For the investment to yield a positive return, we assume $\frac{e^{-rk}}{r}\bar{u}-I>0$. The buyers' indifference condition (33) becomes

$$q^\sigma=\frac{e^{-rk}\bar{u}-rI}{1-\sigma}+rAs^\sigma+q\sigma As^{\sigma-1}. \tag{37}$$

where, for convenience of notation, we substituted q for q_t^0.

Proposition 8 *Assume $\sigma(1-e^{-\omega k})^\sigma>1-e^{-\omega\sigma k}$. Then,*

$$\begin{aligned} s^* &= [\frac{e^{-rk}\bar{u}-rI}{(1-\sigma)^2A^{\frac{-\sigma}{1-\sigma}}-(1-\sigma)rA}]^{-1/\sigma} \\ q^* &= A^{\frac{1}{\sigma-1}}s^* \end{aligned}$$

For $s\geq s^*$ but sufficiently close to s^*, seller's supply $q_t^0=\eta(s_t)$ is defined by (37) and declining in s_t. For s sufficiently large, $q_t^0=\eta(s_t)$ is increasing in s_t.

We depict the equilibrium time path for supply in Fig. 7, as well as the buyers' optimal path. The latter involves just choosing the highest supply path such that (i) prices are equal in present value and (ii) the stock remaining at T^* is consumed during the technology transition period. The equilibrium s^* is, like in the undiscounted case, exactly equal to the buyers' optimal s^* because, due to CRRA, in the post-investment phase the seller supplies a competitive path in both cases. In fact, the CRRA formulation implies unit demand elasticity which eliminates the seller's ability to discriminate buyers' in different periods after the investment. The two paths in Fig. 6 are therefore identical during the technology transition periods, starting at T^* and T, respectively. However, before investment, the strategic seller can discriminate buyers in different periods according to (37) and delay the arrival of the substitute as in the undiscounted case.

We find the equilibrium s^* in the Proposition by using $W^{I\prime}(s^*) = u'(q)$, which defines q^*, in (37) and noting that the buyers' indifference can hold only if $\sigma(1 - e^{-\omega k})^\sigma > 1 - e^{-\omega\sigma k}$. This latter condition can be seen as a restriction on rk; if either discount rate or period k is sufficiently large, investment will take place immediately without any period of strategic interaction. Given this condition, it is straightforward to verify that $q_t^0 = \eta(s_t)$ defined by (37) is decreasing in s for $s > s^*$.[23]

Finally, we note that equilibrium supply $q_t^0 = \eta(s_t)$ cannot satisfy the buyers' indifference (37) for a stock sufficiently large. The reason is that seller's unrestricted supply policy, which would be followed in the absence of the substitute, is increasing in s and thus at some point above $q_t^0 = \eta(s_t)$ defined by (37). Thus, for large stock levels, the seller prefers to sell more than needed to prevent the buyer from investing (although not the same quantity as the unrestricted seller). This explains the early part of the equilibrium sales path in Fig. 7.

6 Concluding remarks

In this paper, we considered strategic interactions between sellers of depletable resource and consumers who have interests in ending their dependence on the resource. We modeled the situation using a framework that departs from explicit bargaining but allows offers and responses such that neither party is in explicit leadership. The approach seems relevant since there is significant coordination of actions on both sides of the market, but at the same time explicit cooperation of the two sides is not feasible by the difficulty of enforcing international agreements. The key question in the relationship is when to start

[23] Condition (37) implicitly defines two values of q given $s > s^*$. The equilibrium strategy must satisfy $dV'(s)/dq < 0$ where $V'(s)$ is given by (31) and evaluated at $(s, q) = (s^*, q^*)$. Condition $\sigma(1 - e^{-\omega k})^\sigma > 1 - e^{-\omega\sigma k}$ ensures that this holds and implies that the lower trajectory ending at (s^*, q^*) is the equilibrium strategy.

the process ending the resource dependence, that is, when to change the demand. The process changing the demand takes time and therefore a potentially significant fraction of the resource has to be saved for the transition period. Our insights to the problem follow from this simple allocation problem.

The main insight from our analysis is that producers' market power is reduced over time as continuing the relationship becomes more costly to consumers when the stock available for the demand transition is depleted. This means that change in demand becomes more relevant as a choice, leading to the conclusion that producers must increase supplies over time. When information about the size of the remaining reserve is private, we found that the continued relationship is costly to consumers not only because of the stock depletion but also because of a possible supply shock. The possibility arises from small sellers' incentive to mimic large sellers' supply policies and delay the demand change by more than what their stock size justifies.

What are the main lessons from these results for understanding the oil market? First, we believe it is the insight that energy technology policies in oil-importing countries can act as an increasingly effective strategic instrument, destroying in part producers scarcity rents. While in general this insight is not new, our approach, where the transition is not a one-time event, is the first to deliver explicitly increasing supplies in a stationary market environment.

Second, OPEC's market power must not be underestimated because of reserve uncertainty and the related possibility of future scarcity when stocks are much lower than expected, and the fact importing countries must rely on these stocks during a period of energy infrastructure change. While OPEC may not be cohesive enough for such a maneuver, individual member countries have stocks large enough such that an unexpected shortfall in estimated reserves can permanently affect the oil market. In particular, future research might benefit from considering market power in the changing oil market where production shifts towards unconventional energy sources, as easily exploitable conventional oil stocks must at some point become scarce. When moving to renewables and unconventional oil, the market becomes more capacity constrained when facing short run shocks, potentially increasing market power of those holding the remaining conventional oil stocks.

On a theoretical level, there are some obvious extensions. Adding a fringe of competitive producers would reduce the seller's market power in a rather straightforward way; the fringe would free-ride on the seller's market power by selling first when the prices are high. Uncertainty about the technology transition period would affect the precise timing of investment and the level of the supply path, but not the basic insights. A less straightforward extension is a reversed asymmetric information situation where the buyer side privately knows whether the adoption decision has been made but the resource stock size is public information. Alternatively, under the R&D interpretation, the buyer privately knows the state of the technology. We leave these interesting topics open for future research.

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Figure 1: Determination of socially optimal supply

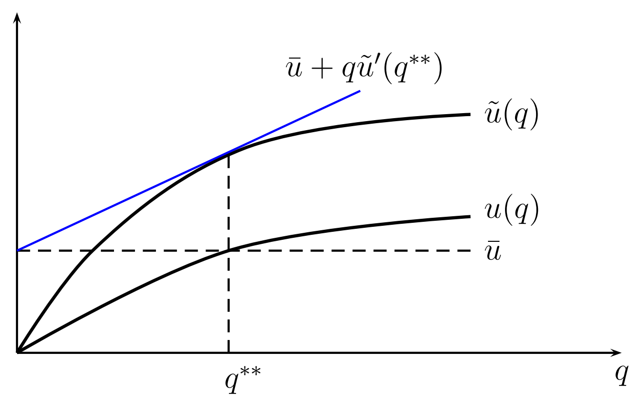

Figure 2: Seller's value function

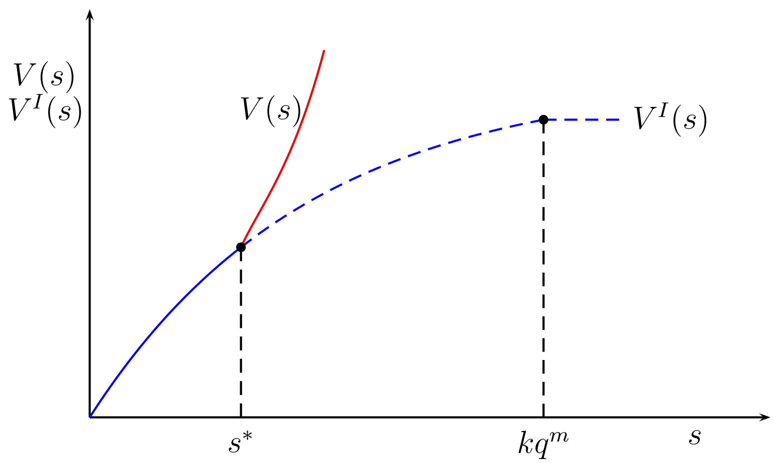

Figure 3: Determination of equilibrium q_t^0

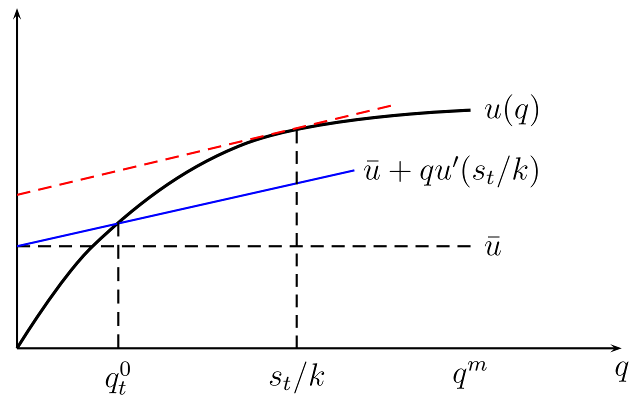

Figure 4: Equilibrium and buyers' optimal supply

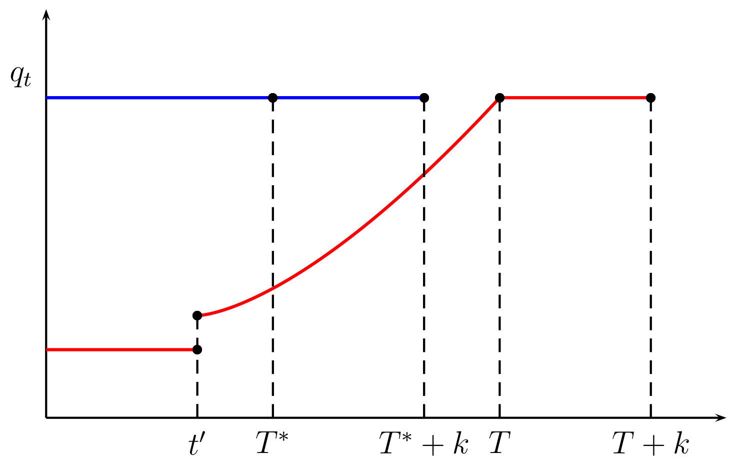

Figure 5: Unobserved reservoir level

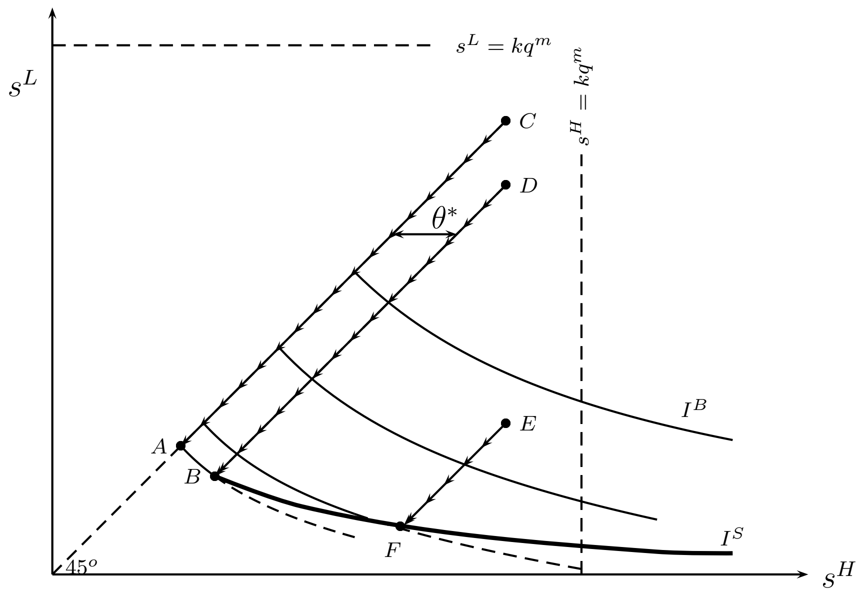

Figure 6: Risky equilibrium supply

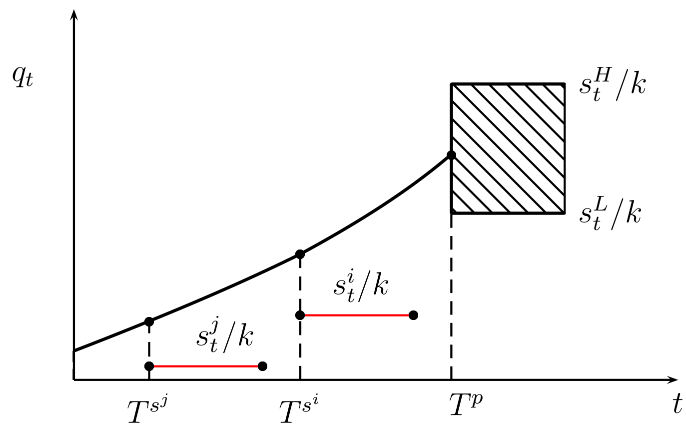

Figure 7: Equilibrium supply path under discounting